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US heavy ion beam research for high energy density physics applications and fusion

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Abstract. Key scientific results from recent experiments, modeling tools, and heavy ion accelerator research are summarized that explore ways to investigate the properties of high energy density matter in heavy-ion-driven targets, in particular, strongly-coupled plasmas at 0.01 to 0.1 times solid density for studies of warm dense matter, which is a frontier area in high energy density physics. Pursuit of these near-term objectives has resulted in many innovations that will ultimately benefit heavy ion inertial fusion energy. These include: neutralized ion beam compression and focusing, which hold the promise of greatly improving the stage between the accelerator and the target chamber in a fusion power plant; and the Pulse Line Ion Accelerator (PLIA), which may lead to compact, low-cost modular linac drivers.

1. INTRODUCTION

Research in the U.S. heavy ion fusion program emphasizes the physics of ion beam compression in space and time that is required to achieve high energy density and fusion conditions [1, 2]. This paper briefly summarizes major recent scientific and technological accomplishments in the Heavy Ion Fusion Virtual National Laboratory (HIF-VNL), including advances in analytical and simulation studies (Sec. 2), experimental investigations of neutralized drift compression and transverse focusing, electron cloud effects, and multiple beamlet merging (Sec. 3), and configuration optimization studies for investigations of the properties of warm dense matter (Sec. 4).

2. ADVANCES IN THEORY AND MODELING

Simulation tools for intense ion beams [3-6] have enjoyed considerable development over the past several years. This has enabled studies of the new regimes required for high energy density physics and warm dense matter studies, and the tools and numerical techniques are also proving very useful for a broad range of accelerator physics and particle trap applications.

2.1 New Simulation Capabilities

***Adaptive mesh refinement (AMR)*:** Commonly applied to fluid simulations, VNL researchers have pioneered AMR integration with particle-in-cell (PIC) simulation methods. This has required analysis and development to minimize non-physical self-forces [7], as well as the consideration of efficiency and implementation details [8].

***Electron cloud and gas "roadmap"*:** A comprehensive set of models governing the interaction of positively-charged beams with stray electron "clouds" (e-clouds) and gas has been developed and implemented [9] in the WARP code [10]. Secondary electron emission from walls, charge exchange, neutral emission, and other processes are included [11]. The CMEE package [12] encapsulates several important plasma-wall interaction physics effects.

***Large time-step particle advance*:** In recent studies we examined the effects of prescribed electrons on the ion dynamics [13]. For self-consistent simulations including electron motion, a "mover" has been developed that interpolates between the full particle dynamics and drift kinetic models. It enables use of a time-step size constrained by the electron bounce time in the electrostatic potential well, thereby offering a computer-time reduction of one-to-two orders- of-magnitude [14, 15].

2.2 Basic Beam Physics Studies

***Ionization, charge exchange and stripping cross sections*:** Ion-atom charge-changing cross sections are needed in many applications employing the propagation of fast ions through matter. A hybrid method has been developed for calculation of the charge-changing cross sections of ions or atoms by fast ions by combining the quasi-classical approach and the Born approximation of quantum mechanics in the regions of impact parameters in which they are valid, and summing the results to obtain the total cross section [16, 17]. This approach has been tested by comparison with available experimental data and full quantum mechanical calculations. A new scaling formula for the ionization and stripping cross section of atoms and ions by fully stripped projectiles has also been developed [16, 18].

***Self-consistent plasma neutralization models*:** Ion beam pulse propagation through a background plasma in a solenoidal magnetic field has been studied analytically and numerically [19, 20]. The neutralization of the ion beam pulse current by the plasma has been calculated using a fluid description for the electrons, extending our previous studies of beam neutralization without an applied magnetic field [21]. Analytical investigations show that the solenoidal magnetic field starts to influence the radial electron motion if electron cyclotron frequency is larger than electron plasma frequency times the speed of the beam ions divided by the speed of light. Particle-in-cell simulations show that the ion beam pulse excites lateral waves, and their detailed properties are being investigated theoretically.

***Beam transport limits*:** Experiments and particle-in-cell (PIC) simulations studying space-charge-dominated beams in quadrupole transport channels show significant emittance growth and particle loss when the undepressed phase advance per lattice period increases beyond about 85°. Recent extensive particle-in-cell simulations and core-particle models have clarified the parametric dependence of the space-charge limit and identified the processes responsible. This work is providing important insights to present-day experiments and will be important for the design of future accelerator systems [22, 23].

2.3 Collective Stability Properties of Intense Ion Beams

We have carried out detailed analytical and numerical studies of the collective processes and beam-plasma interactions affecting intense heavy ion beam propagation [24]. In the acceleration and transport regions, the investigations have included: determination of the conditions for quiescent beam propagation over long distances; the electrostatic Harris-type instability [25, 26] and the electromagnetic Weibel-type instability [27] in strongly anisotropic one-component nonneutral ion beams; and the electron-ion dipole-mode two-stream (electron cloud) instability driven by an (unwanted) component of background electrons using the 3D nonlinear delta-f code BEST [5, 6]. In the plasma neutralization and target chamber regions, collective processes associated with the interaction of the intense ion beam with a charge-neutralizing background plasma have been assessed, including: the electrostatic two-stream instability, the electromagnetic multispecies Weibel instability, and the resistive hose instability [24, 28]. Operating regimes have been identified where the possible deleterious effects of collective processes on beam quality are minimized.

2.4 Studies of Beam Compression and Focusing

After acceleration, the beam pulse duration is reduced using longitudinal drift compression (a longitudinal velocity gradient or "tilt" is imposed on the beam, and it is then allowed to drift axially). For fusion energy applications, either un-neutralized [29-31] or neutralized [32-39] compression may be considered. In the un-neutralized case, to describe the drift compression dynamics and the final focus of the beam particles to a common axial plane and prescribed focal spot size, a warm-fluid model has been employed to describe the longitudinal dynamics of drift compression, coupled nonlinearly to envelope equations that describe the self-consistent transverse dynamics and focusing of the ion beam as it propagates through the quadrupole focusing lattice [30, 31]. This robust model is capable of describing the layout of the magnet lattice, the drift compression phase, and the final focus dynamics for a wide range of system parameters and velocity tilt pulse shapes [30, 31].

For near-term high energy density physics applications, with corresponding short-pulse requirements on target, the beam must be charge neutralized during compression. Simulations have shown that large compression factors, limited only by the beam thermal spread, the accuracy of the compressing waveform, and the completeness of neutralization, can be achieved [32]. Figure 1 shows an example with 120X axial compression and transverse focusing provided by a solenoid.

Simulations and analysis have also been carried out [33-35] in support of the Neutralized Drift Compression Experiment (NDCX) described in Sec. 3, and neutralized transverse focusing has been studied in simulations for the general case [36] and for experiments in the Neutralized Transport Experiment (NTX) [37, 38] described in Sec. 3. Finally, for the case of neutralized drift compression, a fully kinetic model based on the Vlasov equation has been developed that describes the longitudinal compression and transverses focusing of an intense ion charge bunch propagating through a background plasma that provides complete charge and current neutralization in a solenoidal magnetic field [39].

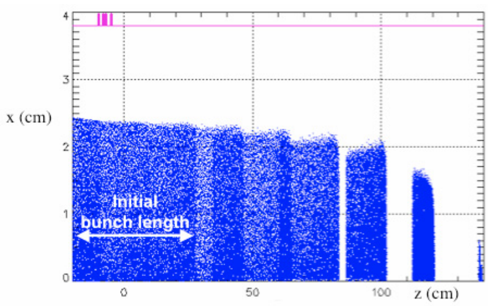

Figure 1. LSP simulation of neutralized drift compression, showing snapshots of a ramped 220-390 keV K^+ ion charge bunch injected into a 1.4-m - long plasma column, at different times (superimposed). The background plasma density is 10X that of initial beam density [32].

3. EXPERIMENTAL ADVANCES IN ION BEAM FOCUSING AND COMPRESSION

3.1 Neutralized Transport Experiment

Significant technical progress has been made in the transverse compression and focusing of intense ion beams in the Neutralized Transport Experiment (NTX) [38, 40]. In NTX, an unneutralized ion beam pulse passes through a finite-length plasma (plasma plug). Plasma electrons are extracted from the plasma into the beam and provide partial charge and current neutralization, reducing the transverse size of the beam at the focal spot.

The partially neutralized beam pulse is then transported through a volumetric plasma region for further charge neutralization and transverse compression, thereby making an even smaller smaller spot size. Figure 2 shows experimental measurements of a more than 10 X reduction of the focal spot size, which is consistent with particle-in-cell simulations [41]. Both theory and experiment indicate that the neutralized beam focal spot size depends on the convergence angle, beam energy, axial position, and head-to-tail variation of the beam parameters, but not significantly on variations in the beam perveance (proportional to beam current).

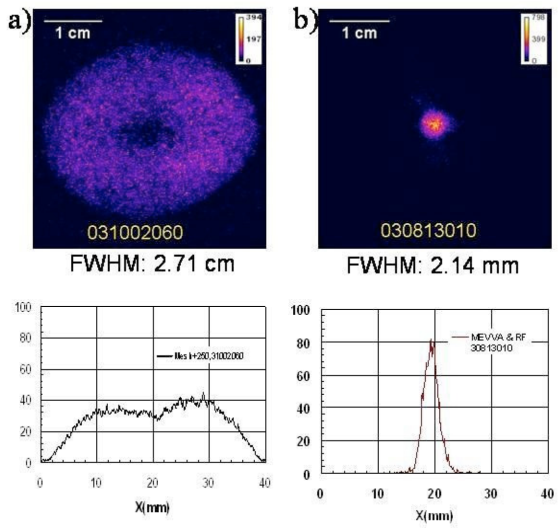

Figure 2. (a) Without charge neutralization, the beam radius in the 24 mA NTX beam at the nominal 1m focal distance is14.7mm. (b) As the NTX beam is charge neutralized by passing it through the pulsed plasma plug and the RF-produced volumetric plasma, the beam radius decreases to 1.3 mm.

3.2 Neutralized Drift Compression Experiment

To compress the axial length as well as the transverse radius of an intense ion charge bunch, the Neutralized Drift Compression Experiment (NDCX) facility began operation in December, 2004. A 300 keV, 25-milliamp K^+ ion beam is given a head-to-tail energy variation (or 'velocity tilt') using a tilt-core induction cell, and then allowed to drift-compress axially along a pre-formed background plasma column. Neutralized drift compression simulations [42] show that the minimum compressed pulse duration is limited only by the accuracy of the applied velocity tilt and the longitudinal velocity spread of the beam. The NDCX beamline consists of an ion beam injector, four quadrupole magnets for radial beam focusing, a tilt-core induction cell to provide a head-to-tail velocity ramp for longitudinal compression, followed by a 1.3 m-long neutralized drift compression section to provide space-charge neutralization during axial compression. Experimentally, nearly ideal velocity-tilt waveforms have been obtained by careful optimization using fourteen independent variations of the tilt-core modulator. Optical phototube and Faraday cup diagnostics show greater than 50 X axial compression of the beam pulse with charge neutralization. The ultimate objective of experiments on NDCX is to understand the underlying physics limits to neutralized beam compression and focusing, in order to develop optimized configurations and operating scenarios for application to high energy density physics studies of warm dense matter and inertial fusion energy.

3.3 Electron Cloud Physics in the High Current Experiment

Electron clouds and a rise in the gas pressure can limit the performance of many major accelerators and may also limit future heavy ion drivers for high energy density physics and fusion. These issues are being studied experimentally using a 1 MeV K^+ heavy ion beams [43] on the High Current Experiment (HCX), together with self-consistent numerical simulations and theoretical studies [44]. Electrons can be generated from three sources: ionization of residual gas; emission from the beam tube; and (in a linac) by emission from the end wall, each of which can be measured. Gridded-ion collectors (GIC) measure the current of expelled ions from the ionization of gas [45], and flush collectors measure the emission of electrons from the beam tube. Separately measured are the electron emission coefficients near grazing incidence, so that the beam halo loss necessary to produce the corresponding current can be determined. The third source of electrons, the linac end wall, is measured by positively-biased clearing electrode rings in drift regions between the magnets. This source of electrons is controlled by a negatively-biased electron suppressor ring that prevents end-wall-emitted electrons from reaching the quadrupole magnets.

Diagnostics to measure the accumulation of electrons include a retarding potential analyzer that can measure either the ion or the electron energy distribution functions in the drift regions between quadrupole magnets [46, 47]. Electron effects on the ion beam are observable in HCX in four quadrupoles provided the beam is inundated with electrons from the end wall by turning off the electron suppressor. In this case, the ions develop a “Z”-shaped (X X’) phase space as shown in Fig. 3. Self-consistent numerical

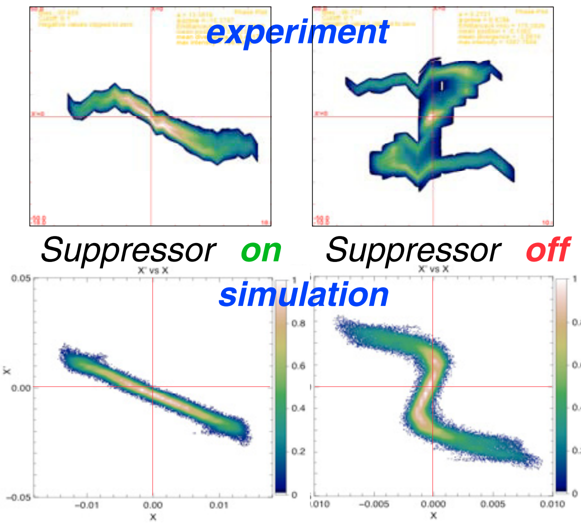

Figure 3. Optical slit scanner plots of the ion beam phase space (X, X’). (a) Experiment with the electron suppressor on. (b) Experiment with the electron suppressor off. (c) Numerical simulation for the electron suppressor on. (d) Simulation for the electron suppressor off.

simulations provide semi-quantitative agreement with the experimental results [44, 48]. Quantitative agreement between the measured currents to the clearing electrodes in the last two drift regions between the quadrupole magnets has also been obtained with the simulations when the electron suppressor is turned off. It is found that including secondary electron effects, in addition to the primary electrons from ion impact, is essential. The secondary electron model is determined from the POSINST code [49].

3.4 Development of Advanced Injectors

The Converging - Beamlets Experiment on the 500-kV test stand at LLNL (STS-500) was successfully completed in 2005. In operation up to 400 keV beam energy at the designed beam current of near 80 mA, the beam pulses were reproducible without voltage breakdown issues. This concluded several years of effort in the development of an advanced, compact, high-current injector for heavy ion fusion drivers. This experiment has validated the multibeamlet injector concept, producing high-brightness, high-current beams using a very compact injector. This adds a new injector option for heavy ion accelerators which is especially important in the context of multiple-beam accelerators, where the expense and spatial extent of the injectors for the multiple beams are significant cost and physics drivers. Simulations using WARP3d were used to design the experiments [50], and results are in good agreement with predictions.

3.5 Advanced Pulse Line Ion Accelerator

For high energy density physics studies of warm dense matter, the ion beam entering the accelerator is (ideally) shorter in pulse duration, with a higher line-charge density, than previously assumed for inertial fusion energy applications. Several front-end accelerator approaches are possible. One very attractive architecture is the Pulse Line Ion Accelerator (PLIA) concept [51, 52]. Experiments have recently been initiated at LBNL to test the PLIA [51, 53] in which a ramped, high-voltage pulse is applied at the input of a helical pulse-line structure (Fig. 4). The resulting traveling-wave pulse on the line can accelerate an ion bunch to energies much greater than the peak voltage applied to the line. It is expected that an axial acceleration gradient of several MeV per meter, with realistic helix parameters, is achievable. Initial experimental tests of the principle of the PLIA are promising, and further experiments are underway.

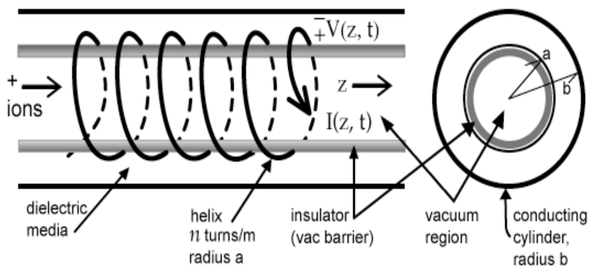

Figure 4. Schematic of the helical pulse-line structure.

4. OPTIMIZED CONFIGURATIONS FOR WARM DENSE MATTER

Heating a target foil to warm dense matter conditions using an ion beam requires high intensity [1, 2]. Our approach to achieve high intensity is to compress the beam pulse in both space and time. By consideration of ion beam phase-space constraints, simple equations of state, and relations for ion stopping, conditions at the target foil can be estimated [54, 55]. As an energetic ion passes through matter its energy loss rate varies with its energy, and has a maximum at the so-called Bragg peak [56]. For an ion passing through solid aluminum (initially at room temperature) over a range of ion mass A from 4 to 126 amu, the energy loss at this peak of the dE/dX curve dE/dX_{max}) increases with Anearly linearly, $(dE/dX_{max} \sim A^{1.1})$ and the energy E at the peak increases nearly quadratically with A (E [at dE/dX_{max}] $\sim A^{1.8}$) [54].

In Ref. [55] it is shown that the target temperature uniformity can be maximized in simple planar targets if the particle energy reaches the maximum in dE/dX when the particle has reached the center of the foil. Choosing ion energies that maximize dE/dX also efficiently uses the investment of energy into the beam. For a specified fractional deviation in target temperature (assuming the energy is deposited in a time sufficiently short that no hydrodynamic, radiative, or other cooling has occurred), the energy at which the ion must enter and exit the foil can be determined. From the curves of dE/dX in Ref. [56] we find that for the entrance energy to have less than a 5% lower energy loss rate relative to the peak in dE/dX, the inequality $\Delta E/E < \approx 1.0$ is required, where ΔE is the difference in ion energy between entering and exiting the foil, and E is the energy at which dE/dX is a maximum. The spatial width of the foil Z, for a 5% temperature non-uniformity is then given by

$$Z = \Delta E/(\rho dE/dX) \approx 0.77\mu \quad A^{0.73}(\rho_{al}\rho) \tag{1}$$

Here, we have used $\rho_{\mathrm{al}} = 2.7\,\mathrm{g/cm}^3$. By employing materials of low density such as metallic foams, the width of the foil can be relatively large, which allows longer heating times and also accesses interesting densities.

For an instantaneously heated foil target, a rarefaction wave propagates inward at a speed characterized by the sound speed c_{s}, while matter flows outward at about 2 c_{s} (for a 1D gas) [57]. Therefore, for measurement of material properties, heating needs to occur on a time scale such that the rarefaction wave does not progress so far as to render the full density region of the foil smaller than some minimum diagnosable spatial scale over the duration of the pulse. Figure 5 illustrates the results of a simulation using the radiation transport and hydrodyamics code HYDRA [58, 59] for an intense ion beam heating a metal foam. The simulation shows that the pulse duration is short enough to allow the central temperature to reach its maximum value of about 5 eV, over the course of the pulse. Table 1 summarizes illustrative beam parameters for various ion masses that would also allow a 5% energy variation over the course of a pulse for five different ion species, and would achieve a 10 eV central temperature. The table indicates the general trend that as A increases the ion energy increases, and the total current requirement is reduced.

Detailed studies show that maintenance of both transverse and longitudinal high beam quality will be essential for achieving warm dense matter conditions using ion beams [54].

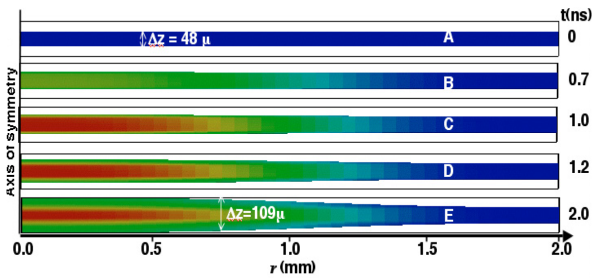

Figure 5. The evolution of a 48 μ thick aluminum 10% solid density aluminum foam, heated by a 20 MeV, 330 A, 1 ns, Ne^+ ion beam, shown at five different times (A through E) from 0 to 2 ns, obtained using the HYDRA code [58]. False color temperatures are shown (red = 5 eV, yellow = 4 eV green = 3 eV, turqoise = 2 eV, and blue <= 0.1 eV). At 1 ns, the region of expanding material is limited but has significantly broadened by 2 ns. The beam is impinging from the top and has a radius of 1 mm, and the peak in the energy loss rate of the beam is located approximately halfway into the foil [59].

Table 1. Parameters for five different ion beam species such that the central temperature of a 10% solid density aluminum foil reaches 10 eV.

Beam Ion	Z	A (amu)	Energy at Bragg Peak (MeV)	dE/dX at Bragg Peak (MeV-cm2/mg)	Foil Entrance Energy (app) (MeV)	Delta z for 5% T variation (10% solid Al) (microns)	Beam Energy for 10 eV (J/mm2)	t_hydro= delta z/(2 cs) at 10 eV (ns)	Beam Power per sq. mm (GW/mm2)	Beam current for 1 mm diameter spot (A)
Li	3	6.94	1.6	2.68	2.4	22.1	3.3	0.5	6.1	1990.6
Na	11	22.99	15.9	11	23.9	53.5	8.0	1.3	6.1	200.3
K	19	39.10	45.6	18.6	68.4	90.8	13.6	2.2	6.1	69.8
Rb	37	85.47	158.0	39.1	237.0	149.7	22.4	3.7	6.1	20.2
Cs	55	132.91	304.0	59.2	456.0	190.2	28.5	4.7	6.1	10.5

5. CONCLUSIONS

This paper has summarized key scientific results from recent experiments, modeling tools, and heavy ion accelerator research that explore ways to investigate the properties of high energy density matter in heavy-ion-driven targets, in particular, strongly-coupled plasmas at 0.01 to 0.1 times solid density for studies of warm dense matter, which is a frontier area in high energy density physics, Pursuit of these near-term objectives has resulted in many innovations that will ultimately benefit heavy ion inertial fusion energy.

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